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Final Report: Continuation: Terahertz and Microwave Devices Based on the Photo-Excited Low Dimensional Electronic System

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W911NF-10-1-0450

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
Ramesh G. Mani

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Georgia State University Research Foundati
PO Box 3999

Atlanta, GA 30302 -3999

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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
This experimental project funded by the ARO under grant # W911NF-10-1-0450 was concerned with the study of the electrical properties of low dimensional systems in a steady state non-equilibrium condition that is realized by photo-exciting the system with electromagnetic waves in the microwave and THz parts of the radiation spectrum, in the presence of a weak magnetic field. In this regime, it has been found, for example, that dissipative electrical resistance of a semiconductor can vanish over broad magnetic field intervals, as novel magnetoresistance

15. SUBJECT TERMS
Terahertz, Microwaves, 2 Dimensional electron systems, sensors, magnetotransport, reflection, spin resonance,

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Report Title

Final Report: Continuation: Terahertz and Microwave Devices Based on the Photo-Excited Low Dimensional Electronic System

ABSTRACT

This experimental project funded by the ARO under grant # W911NF-10-1-0450 was concerned with the study of the electrical properties of low dimensional systems in a steady state non-equilibrium condition that is realized by photo-exciting the system with electromagnetic waves in the microwave and THz parts of the radiation spectrum, in the presence of a weak magnetic field. In this regime, it has been found, for example, that dissipative electrical resistance of a semiconductor can vanish over broad magnetic field intervals, as novel magnetoresistance oscillations are induced by photo exciting a high mobility low dimensional electron system. This research aimed to advance the understanding of such radiation-induced phenomena in the two-dimensional electron system, while helping to develop new concepts for terahertz devices.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/30/2011	2.00	A. Kriisa, R. G. Mani, W. Wegscheider. Hall effects in doubly connected specimens, IEEE Transactions on Nanotechnology, (01 2011): 179. doi:
08/30/2011	8.00	Jesús Iñarrea, R. Mani, W. Wegscheider. Sublinear radiation power dependence of photoexcited resistance oscillations in two-dimensional electron systems, Physical Review B, (11 2010): 0. doi: 10.1103/PhysRevB.82.205321
08/30/2011	7.00	W. Wegscheider, R. G. Mani. Comparative Study of Microwave Radiation-Induced Magnetoresistance Oscillations in GaAs/AlGaAs Devices, IEEE Transactions on Nanotechnology, (01 2011): 0. doi: 10.1109/TNANO.2010.2052285
08/30/2011	6.00	R. Mani, A. Ramanayaka, W. Wegscheider. Observation of linear-polarization-sensitivity in the microwave-radiation-induced magnetoresistance oscillations, Physical Review B, (8 2011): 0. doi: 10.1103/PhysRevB.84.085308
08/30/2011	5.00	R. Mani, W. Wegscheider, A. Ramanayaka. Microwave-induced electron heating in the regime of radiation-induced magnetoresistance oscillations, Physical Review B, (4 2011): 0. doi: 10.1103/PhysRevB.83.165303
08/30/2011	4.00	Aruna Ramanayaka, Ramesh Mani. Transport study of the Berry phase, resistivity rule, and quantum Hall effect in graphite, Physical Review B, (10 2010): 0. doi: 10.1103/PhysRevB.82.165327
08/30/2012	9.00	A. Ramanayaka, R. Mani, J. Iñarrea, W. Wegscheider. Effect of rotation of the polarization of linearly polarized microwaves on the radiation-induced magnetoresistance oscillations, Physical Review B, (05 2012): 0. doi: 10.1103/PhysRevB.85.205315
08/30/2012	10.00	John Hankinson, Ramesh G. Mani, Claire Berger, Walter A. de Heer. Observation of resistively detected hole spin resonance and zero-field pseudo-spin splitting in epitaxial graphene, Nature Communications, (08 2012): 0. doi: 10.1038/ncomms1986
10/05/2013	12.00	R. G. Mani, W. Wegscheider, Tianyu Ye. Remotely sensed transport in microwave photoexcited GaAs/AlGaAs two-dimensional electron system, Applied Physics Letters, (06 2013): 242113. doi: 10.1063/1.4812188
10/05/2013	13.00	R. G. Mani, A. N. Ramanayaka, Tianyu Ye, M. S. Heimbeck, H. O. Everitt, W. Wegscheider. Terahertz photovoltaic detection of cyclotron resonance in the regime of radiation-induced magnetoresistance oscillations, Physical Review B, (06 2013): 245308. doi: 10.1103/PhysRevB.87.245308
10/05/2013	14.00	Olesya I. Sarajlic, Ramesh G. Mani. Mesoscale Scanning Electron and Tunneling Microscopy Study of the Surface Morphology of Thermally Annealed Copper Foils for Graphene Growth, Chemistry of Materials, (05 2013): 1643. doi: 10.1021/cm400032h
10/05/2013	19.00	R. G. Mani, J. Hankinson, C. Berger, W. A. de Heer. Observation of resistively detected hole spinresonance and zero-field pseudo-spin splittingin epitaxial graphene, Nature Communications, (08 2013): 1. doi:

10/21/2014 20.00 Tianyu Ye, Han-Chun Liu, W. Wegscheider, R. G. Mani. Combined study of microwave-power/linear-polarization dependence of the microwave-radiation-induced magnetoresistance oscillations in GaAs/AlGaAs devices,
Physical Review B, (04 2014): 0. doi: 10.1103/PhysRevB.89.155307

10/21/2014 21.00 R. G. Mani, A. Kriisa. Magneto-transport characteristics of a 2D electron system driven to negative magneto-conductivity by microwave photoexcitation,
Scientific Reports, (12 2013): 0. doi: 10.1038/srep03478

10/21/2014 22.00 Tianyu Ye, R. G. Mani, W. Wegscheider. Remote sensor response study in the regime of the microwave radiation-induced magnetoresistance oscillations,
Applied Physics Letters, (11 2013): 0. doi: 10.1063/1.4829441

10/21/2014 23.00 R. G. Mani, A. Kriisa, W. Wegscheider. Size-dependent giant-magnetoresistance in millimeter scale GaAs/AlGaAs 2D electron devices,
Scientific Reports, (09 2013): 0. doi: 10.1038/srep02747

10/21/2014 24.00 A.N. Ramanayaka, Tianyu Ye, H.-C. Liu, W. Wegscheider, R.G. Mani. Interaction of microwave radiation with the high mobility two-dimensional electron system in GaAs/AlGaAs heterostructures,
Physica B: Condensed Matter, (11 2014): 0. doi: 10.1016/j.physb.2014.03.064

10/21/2014 26.00 Tianyu Ye, Ramesh Mani, Werner Wegscheider. Microwave reflection study of ultra-high mobility GaAs/AlGaAs 2D-electron system at large filling factors,
MRS Proceedings, (01 2014): 0. doi: 10.1557/opl.2014.107

TOTAL: **18**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Talks at March Meetings of American Physical Society (Printed abstract but no proceeding publication)

1. Combined study of microwave-power-dependence and linear-polarization-dependence of the microwave-radiation-induced magnetoresistance oscillations. T. Ye, H-C. Liu, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 59, Abstract: BAPS.2014.Mar. A45.10, March 3, 2014.
2. Size-dependent giant-magnetoresistance in millimeter scale GaAs/AlGaAs devices, R. G. Mani, A. Kriisa, and W. Wegscheider, Bull. Am. Phys. Soc. 59, Abstract: BAPS.2014.Mar.A45.11, March 3, 2014.
3. Study of the phase-shift in the linear-polarization-angle-dependence of the microwave radiation-induced magnetoresistance oscillations in the GaAs/AlGaAs system, H-C. Liu, T. Ye, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 59, Abstract: BAPS.2014.Mar.A45. 12, March 3, 2014.
4. Proximity effect in the 3D topological insulator Bi2Te3, Z. Wang, T. Ye, and R. G. Mani, Bull. Am. Phys. Soc. 59, Abstract: BAPS. 2014.Mar.M41.13, March 3, 2014.
5. Electrically detected spin resonance in epitaxial graphene, R. G. Mani, J. Hankinson, C. Berger, and W. A. de Heer, Bull. Am. Phys. Soc. 58, Abstract: BAPS.2013.MAR.J7.2, March 19, 2013.
6. Study of the phase-shift in the linear-polarization-angle dependence of the microwave radiation-induced magnetoresistance oscillations in the GaAs/AlGaAs system, Han-Chun Liu, T. Ye, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 58, Abstract: BAPS.2013. MAR.A42.2, March 18, 2013.
7. Study of the correlation between microwave reflection and microwave-induced magnetoresistance oscillations in the GaAs/AlGaAs two dimensional electron system, Tianyu Ye, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 58, Abstract: BAPS. 2013.MAR.A42. 1, March 18, 2013.
8. Magnetoresistance in thin Bi2Te3 layers contacted by Indium (In) superconducting electrodes, Zhuo Wang and R. G. Mani, Bull. Am. Phys. Soc. 58, Abstract: BAPS.2013.MAR.J12.4, March 19, 2013.
9. Immense weak localization effect in CVD graphene, O. Sarajlic and R. G. Mani, Bull. Am. Phys. Soc. 58, Abstract BAPS.2013.MAR. W5.11, March 21, 2013.
10. Observation of linear polarization sensitivity in the microwave-radiation induced magneto-resistance oscillations, R. G. Mani, A. Ramanayaka, and W. Wegscheider, Bull. Am. Phys. Soc. 57, Abstract # W24.00010, March 1, 2012.
11. Linear polarization rotation study of the radiation-induced magnetoresistance oscillations, A. Ramanayaka, R. G. Mani, J. Inarrea, and W. Wegscheider, Bull. Am. Phys. Soc. 57, Abstract # W24.00013, March 1, 2012.
12. Microwave reflection study of GaAs/AlGaAs devices in the regime of the radiation-induced magnetoresistance oscillations, Tianyu Ye, A. Ramanayaka, R. G. Mani, J. Inarrea, and W. Wegscheider, Bull. Am. Phys. Soc. 57, Abstract # W24.00009, March 1, 2012.
13. Mesoscale STM study of thermally annealed copper foils, Olesya Sarajlic and R. G. Mani, Bull. Am. Phys. Soc. 57, Abstract # T12. 00006, Feb. 29, 2012.
14. Magnetotransport study of the topological insulator Bi2Te3, P. Kumar, A. Ramanayaka, and R. G. Mani, Bull. Am. Phys. Soc. 57, Abstract # J31.00008, Feb. 28, 2012.
15. Transport study under microwave photoexcitation in epitaxial Graphene, R. G. Mani, J. Hankinson, C. Berger, and W. de Heer, Bull. Am. Phys. Soc. 56, Abstract# x11.00004, March 24, 2011
16. Scanning Tunneling Microscope study of Atomic steps in Gold films on Muscovite Graphite, Olesya Sitnikova and R. G. Mani, Bull. Am. Phys. Soc. 56, Abstract# W21.00004, March 24, 2011
17. Microwave induced electron heating in the regime of the radiation-induced magnetoresistance oscillations, A. Ramanayaka, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 56, Abstract# x11.00003, March 24, 2011
18. Remote sensing of transport in microwave photo-excited magnetoresistance oscillations in the GaAs/AlGaAs system, Tianyu Ye, G. Chand, A. Ramanayaka, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 56, Abstract# x11.00006, March 24, 2011
19. Microwave photo-voltaic oscillations in the GaAs/AlGaAs system, G. Chand, T. Ye, A. Ramanayaka, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 56, Abstract# x11.00011, March 24, 2011

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Talks at MRS Fall and Spring Meetings

1) Resistively detected hole spin resonance in epitaxial graphene, R. G. Mani, J. Hankinson, C. Berger, and W. A. de Heer, 2013 Fall MRS Meeting, Boston, MA. December 2, 2013 [1763133]. RR2.02
2) Microwave Reflection Study of Ultra High Mobility GaAs/AlGaAs 2D-Electron System at Large Filling Factors, Tianyu Ye, R. G. Mani, and W. Wegscheider, 2013 Fall MRS Meeting, Boston, MA. December 4, 2013 [1758111]. T9.05
3) Study of Length Scales Extracted from Weak Localization in CVD Graphene, O. I. Sarajlic and R. G. Mani, 2013 Fall MRS Meeting, Boston, MA. December 5, 2013 [1760756]. RR15.129
4) Resistively detected hole spin resonance in epitaxial graphene, R. G. Mani, J. Hankinson, C. Berger, and W. de Heer, 2014 Spring MRS Meeting, San Francisco, CA. April 24, 2014 [1881293]. OO16.05

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Poster presentations at various conferences

1) Remote sensing of transport under microwave photo-excitation in the two-dimensional electron system (Mo-P-48), T. Ye, A. Ramanayaka, R. G. Mani, and W. Wegscheider, EP2DS19/MSS15 Conference, 7/25 – 7/29 2011, Tallahassee, FL.
2) Microwave-induced electron-heating in the regime of the radiation-induced magnetoresistance oscillations in the GaAs/AlGaAs 2D electron system (Tu-P-82), A. Ramanayaka, R. G. Mani, and W. Wegscheider, EP2DS19/MSS15 Conference, 7/25 – 7/29 2011,

Tallahassee, FL.
3) Method for measuring the electron temperature in microwave photo-excited two-dimensional electron systems, A. Ramanayaka, R. G. Mani, and W. Wegscheider, Nano-DDS 2011 Conference, 8/30/2011, Brooklyn, NY.
4) Microwave reflection from the microwave photo-excited two-dimensional electron system, T. Ye, A. Ramanayaka, R. G. Mani, and W. Wegscheider, Nano-DDS 2011 Conference, 8/30/2011, Brooklyn, NY.
5) Study Of The Electron Temperature In The Microwave Photo-Excited GaAs/AlGaAs Two Dimensional Electron System, A. N. Ramanayaka, R. G. Mani, W. Wegscheider, NPCQS International Workshop on Nonequilibrium Phenomena in Complex Quantum Systems, 23-27 April, 2012, Okinawa, Japan.
6) Concurrent study of microwave reflection and transport in the microwave photo-excited high mobility GaAs/AlGaAs two-dimensional electron system, Tianyu Ye, R. G. Mani, W. Wegscheider, NPCQS International Workshop on Nonequilibrium Phenomena in Complex Quantum Systems, 23-27 April, 2012, Okinawa, Japan.
7) Photoexcited Transport In Graphene, Olesya Sarajlic, R. G. Mani, J. Hankinson, C. Berger, and W. de Heer, NPCQS International Workshop on Nonequilibrium Phenomena in Complex Quantum Systems, 23-27 April, 2012, Okinawa, Japan.
8) Microwave photo-excited transport in epitaxial graphene, R. G. Mani, O. Sarajlic, J. Hankinson, C. Berger, and W. de Heer, 20th International Conference on High Magnetic Fields in Semiconductor Physics (HMF20), 22 – 27 July 2012, Chamonix, France.
9) Microwave reflection and transport in the microwave photo-excited high mobility GaAs/AlGaAs two-dimensional electron system, T. Ye, A. N. Ramanayaka, R. G. Mani, and W. Wegscheider, 20th International Conference on High Magnetic Fields in Semiconductor Physics (HMF20), 22 – 27 July 2012, Chamonix, France.

10) Linear polarization rotation study of the microwave radiation-induced magnetoresistance oscillations in the GaAs/AlGaAs system, A. N. Ramanayaka, T. Ye, H. C. Liu, R. G. Mani, and W. Wegscheider, 20th International Conference on Electronic Properties of Two-dimensional Systems, 1 – 5 July 2013, Wroclaw, Poland.
11) Nonlinear growth in the microwave reflection signal from the GaAs/AlGaAs 2DES in the regime of radiation-induced magnetoresistance oscillations, Tianyu, Ye, R. G. Mani, and W. Wegscheider, 20th International Conference on Electronic Properties of Two-dimensional Systems, 1 – 5 July 2013, Wroclaw, Poland.

12) Magnetotransport studies of the low dimensional electron system, R. G. Mani, DOE-BES Experimental Condensed Matter Physics PI Meeting, 23-25 Sept. 2013, Rockville, MD.

Number of Presentations: 35.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

10/05/2013 15.00 R. G. Mani, W. Wegsheider, A. Kriisa. Topological Hall insulator,
31st International Conference on the Physics of Semiconductors. 20-JUL-12, . : ,

10/05/2013 16.00 R. G. Mani, A. N. Ramanayaka, W. Wegscheider. Observation of linear-polarization-sensitivity in themicrowave-radiation-induced magnetoresistance oscillations,
31st International Conference on the Physics of Semiconductors. 29-JUL-12, . : ,

10/05/2013 17.00 A. N. Ramanayaka, R. G. Mani,, W. Wegscheider. Electron heating due to microwave photoexcitation in thehigh mobility GaAs/AlGaAs two dimensional electron system,
31st International Conference on the Physics of Semiconductors. 29-JUL-13, . : ,

10/05/2013 18.00 Tianyu Ye, R. G. Mani, W. Wegscheider. Study of reflection and transport in the microwavephoto-excited GaAs/AlGaAs two dimensional electron system,
31st International Conference on the Physics of Semiconductors. 29-JUL-13, . : ,

TOTAL: 4

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

- Aruna N. Ramanayaka, The Joseph Hadley Outstanding Advanced Graduate Student Award in Physics & Astronomy - 2012
- Olesya I. Sarajlic, The Outstanding Graduate Student Teaching Award for 2012 – 2013
- Tianyu Ye, The Joseph Hadley Outstanding Advanced Graduate Student Award in Physics & Astronomy - 2014

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
A. N. Ramanayaka	0.25	
T. Ye	0.25	
O. Sarajlic	0.25	
P. Thapa	0.10	
G. Chand	0.10	
Z. Wang	0.10	
H-C. Liu	0.20	
K. Baral	0.10	
FTE Equivalent:	**1.35**	
Total Number:	**8**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
T. Ghanem	0.50
P. Kumar	0.50
FTE Equivalent:	**1.00**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
R. G. Mani	0.08	
FTE Equivalent:	**0.08**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Olesya Sarajlic	0.50	Physics
Megan Smith	0.50	Physics
Alberto Abreus	0.50	Physics
Kenny Lee	0.50	Physics
Jennifer Rehm	0.50	Physics
Terence Fisher	0.50	Physics
FTE Equivalent:	**3.00**	
Total Number:	**6**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 5.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 6.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 5.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 3.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 3.00

Names of Personnel receiving masters degrees

NAME	
A. N. Ramanayaka	
T. Ye	
P. Thapa	
Z. Wang	
O. Sarajlic	
H. C. Liu	
Total Number:	**6**

Names of personnel receiving PHDs

NAME	
A. N. Ramanayaka	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

see attachment below

Technology Transfer

We worked together with Dr. Henry Everitt and Dr. Martin Heimbeck of the Redstone Arsenal to test a series of multiplier based microwave and terahertz souces spanning the range from 100- 750 GHz. The work resulted in the paper: "Terahertz photovoltaic detection of cyclotron resonance in the regime of radiation-induced magnetoresistance oscillations," R. G. Mani, A. Ramanayaka, T. Ye, M. Heimbeck, H. Everitt, and W. Wegscheider, Phys. Rev. B 87, 245308 (2013).

Subject terms: Terahertz, Microwaves, 2 Dimensional electron systems, sensors,

Final report for the period: 13 Sep. 2010 – 12 Nov. 2014
"Terahertz devices based on the photo-excited low dimensional electron system"
Proposal: 58093-EL; W911NF-10-1-0450

R. G. Mani
Department of Physics & Astronomy
Georgia State University
Atlanta, GA 30303

Abstract: This experimental project funded by the ARO under grant # W911NF-10-1-0450 was concerned with the study of the electrical properties of low dimensional systems in a steady state non-equilibrium condition that is realized by photo-exciting the system with electromagnetic waves in the microwave and THz parts of the radiation spectrum, in the presence of a weak magnetic field. In this regime, it has been found, for example, that dissipative electrical resistance of a semiconductor can vanish over broad magnetic field intervals, as novel magnetoresistance oscillations are induced by photo exciting a high mobility low dimensional electron system. This research aimed to advance the understanding of such radiation-induced phenomena in the two-dimensional electron system, while helping to develop new concepts for terahertz devices.

Summary for the period 2013 – 2014:

In the above mentioned period, this funding helped to produce the publications listed below:

1) Combined study of microwave-power/linear polarization dependence of the microwave radiation-induced magnetoresistance oscillations in GaAs/AlGaAs devices, T. Ye, H-C. Liu, W. Wegscheider, and R. G. Mani, Phys. Rev. B 89, 155307 (2014).
2) Interaction of microwave radiation with the high mobility two-dimensional electron system in GaAs/AlGaAs heterostructures, A. N. Ramanayaka, T. Ye, H-C. Liu, W. Wegscheider, and R. G. Mani, Physica B 453, 43-48 (2014).
3) Microwave reflection study of ultra high mobility GaAs/AlGaAs 2D electron system at large filling factors, T. Ye, R. G. Mani, and W. Wegscheider, MRS Proceedings, 1635, pp 69-74 (2014)| doi: 10.1557/opl.2014.107
4) Size-dependent giant-magnetoresistance in millimeter scale GaAs/AlGaAs 2D electron devices, R. G. Mani, A. Kriisa, and W. Wegscheider, Scientific Reports 3, 2747 (2013) | doi:10.1038/srep02747.
5) Magnetotransport characteristics of a two-dimensional electron system driven to negative conductivity by microwave photoexcitation, R. G. Mani and A. Kriisa, Scientific Reports 3, 3478 (2013)| doi:10.1038/srep03478.
6) Remote sensor response study in the regime of the microwave radiation-induced magnetoresistance oscillations, T. Ye, R. G. Mani, and W. Wegscheider, Appl. Phys. Lett. 103, 192106 (2013).

These GaAs/AlGaAs works (4) & (5) received attention by the media. A publication of the press release for this work can be found, for example, at the following links for #4:
http://www.sciencedaily.com/releases/2013/10/131015134926.htm?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+sciencedaily+%28ScienceDaily%3A+Latest+Science+News%29
http://www.nanowerk.com/news2/newsid=32749.php
and at this link for #5:
http://www.sciencedaily.com/releases/2013/12/131211131947.htm

Four conference papers listed below were published in 12/2013 in the Proceedings of the 31th International Conference on the Physics of Semiconductors, which was held in Zurich, Switzerland, in summer 2012:

- Electron heating due to microwave photoexcitation in the high mobility GaAs/AlGaAs two dimensional electron system, A. N. Ramanayaka, R. G. Mani, and W. Wegscheider, in the Proceedings of the 31th International Conference on the Physics of Semiconductors, AIP Conf. Proc. 1566, 233 (2013); doi: 10.1063/1.4848371

- Observation of linear-polarization sensitivity in the microwave radiation-induced magnetoresistance oscillations, R. G. Mani, A. N. Ramanayaka, and W. Wegscheider, in the Proceedings of the 31th International Conference on the Physics of Semiconductors, AIP Conf. Proc. 1566, 235 (2013); doi: 10.1063/1.4848372

- Study of reflection and transport in the microwave photo-excited GaAs/AlGaAs two dimensional electron system, T. Ye, R. G. Mani, and W. Wegscheider, in the Proceedings of the 31th International Conference on the Physics of Semiconductors, AIP Conf. Proc. 1566, 291 (2013); doi: 10.1063/1.4848395

- Topological Hall Insulator, A. Kriisa, R. G. Mani, and W. Wegscheider, in the Proceedings of the 31th International Conference on the Physics of Semiconductors, AIP Conf. Proc. 1566, 195 (2013); doi: 10.1063/1.4848352

In the summer of 2013, the group presented a poster at the 22th International Materials Research Conference in Cancun, Mexico:

- Microwave Reflection from the Microwave Photo-Excited High Mobility GaAs/AlGaAs Two-Dimensional Electron System, Tianyu Ye, R. G. Mani, and W. Wegscheider, XXII International Materials Research Conference, 11 – 15 August 2013, Cancun, Mexico.

There were also two talks by the PI, Ramesh Mani, at the same conference:

- Resistively Detected Spin Resonance and Zero-field Pseudo Spin Splitting in Epitaxial Graphene. XXII International Material Research Congress 2013 (IMRC 2013), August 11 -15, 2013. Cancun, Mexico.

- Linear polarization rotation study of the microwave-induced magnetoresistance oscillations in the GaAs/AlGaAs system. XXII International Material Research Congress 2013 (IMRC 2013), August 11 -15, 2013. Cancun, Mexico.

The PI also presented a poster at the DOE Condensed Matter Physics meeting:

- Magnetotransport studies of the low dimensional electron system, R. G. Mani, DOE-BES Experimental Condensed Matter Physics Meeting, 23-25 Sept. 2013, Rockville, MD.

There were two group posters and one talk by the PI, Ramesh Mani, at the Fall MRS Meeting in Boston, MA:

- Microwave Reflection Study of Ultra High Mobility GaAs/AlGaAs 2D-Electron System at Large Filling Factors, Tianyu Ye, R. G. Mani, and W. Wegscheider, 2013 Fall MRS Meeting, Boston, MA. December 4, 2013 [1758111]. T9.05 (poster)
- Study of Length Scales Extracted from Weak Localization in CVD Graphene, O. I. Sarajlic and R. G. Mani, 2013 Fall MRS Meeting, Boston, MA. December 5, 2013 [1760756]. RR15.129 (poster)
- Resistively detected hole spin resonance in epitaxial graphene, R. G. Mani, 2013 Fall MRS Meeting, [1763133] RR2.02, Boston, MA December 2, 2013.(talk)

There were four contributed talks at the 2014 March Meeting of the American Physical Society at Denver, CO:

- Combined study of microwave-power-dependence and linear-polarization-dependence of the microwave-radiation-induced magnetoresistance oscillations. T. Ye, H-C. Liu, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 59, Abstract: BAPS.2014.Mar.A45.10, March 3, 2014.
- Size-dependent giant-magnetoresistance in millimeter scale GaAs/AlGaAs devices, R. G. Mani, A. Kriisa, and W. Wegscheider, Bull. Am. Phys. Soc. 59, Abstract: BAPS.2014.Mar.A45.11, March 3, 2014.
- Study of the phase-shift in the linear-polarization-angle-dependence of the microwave radiation-induced magnetoresistance oscillations in the GaAs/AlGaAs system, H-C. Liu, T. Ye, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 59, Abstract: BAPS.2014.Mar.A45.12, March 3, 2014.
- Proximity effect in the 3D topological insulator Bi2Te3, Z. Wang, T. Ye, and R. G. Mani, Bull. Am. Phys. Soc. 59, Abstract: BAPS.2014.Mar.M41.13, March 3, 2014.

The PI gave the following talk at the Spring Meeting of the MRS at San Francisco, CA.

- Resistively detected hole spin resonance in epitaxial graphene, R. G. Mani, 2014 Spring MRS Meeting, [1881293] OO16.05, San Francisco, CA. April 24, 2014.

The PI presented a poster at the 56th Electronic Materials Conference in Santa Barbara, CA:

- Growth of graphene and boron nitride by Chemical Vapor Deposition, R. G. Mani, 56th Electronic Materials Conference, Santa Barbara, CA. 25 – 27 June, 2014.

There were a number of talks and posters at the International Conference on the Physics of Semiconductors in Austin, TX and at the HMF -21 conference in Panama City, FL. Since these conferences occurred after July 31, we will report these items in the next annual report.

In the fall semester of 2013, graduate student Zhuo Wang defended her MS research in a talk entitled:

- Zhuo Wang, MS (Physics) – 11/2013: “Proximity effect in the 3D topological insulator Bi2Te3”

Shortly thereafter, graduate student Olesya Sarajlic defended her MS thesis in a talk entitled:

- Olesya Sarajlic, MS (Physics) – 11/2013: “Mesoscale Scanning Electron and Tunneling Microscopy Study of the Surface Morphology of Thermally Annealed Copper Foils for Graphene Growth”

In the spring semester of 2014, graduate student Han-Chun Liu defended his MS research in a talk entitled:

- Han-Chun Liu, MS (Physics) – 04/2014: “Study of the phase-shift in the angle-dependence of the microwave-induced magnetoresistance oscillations”

Summary of Publications:

- *Remote sensor response study in the regime of the microwave radiation-induced magnetoresistance oscillations, T. Ye, R. G. Mani, and W. Wegscheider, Appl. Phys. Lett. 103, 192106 (2013).*

A concurrent remote sensing and magneto-transport study of the microwave excited two dimensional electron system (2DES) at liquid helium temperatures was carried out using a carbon detector to remotely sense the microwave activity of the 2D electron system in the GaAs/AlGaAs heterostructure during conventional magneto-transport measurements. Various correlations were observed and reported between the oscillatory magneto - transport and the remotely sensed reflection. In addition, the oscillatory remotely sensed signal was shown to exhibit a power law type variation in its amplitude, similar to the radiation-induced magnetoresistance oscillations.

- *Size-dependent giant-magnetoresistance in millimeter scale GaAs/AlGaAs 2D electron devices, R. G. Mani, A. Kriisa, and W. Wegscheider, Scientific Reports 3, 2747 (2013) | doi:10.1038/srep02747.*

Large changes in the electrical resistance induced by the application of a small magnetic field are potentially useful for device-applications. Such Giant Magneto-Resistance (GMR) effects also provide new insights into the physical phenomena involved in the associated electronic transport. This study examined a "bell-shape" negative GMR that grows in magnitude with decreasing temperatures in mm-wide devices fabricated from the high-mobility GaAs/AlGaAs 2-Dimensional Electron System (2DES). Experiments showed that the span of this magnetoresistance on the magnetic-field-axis increases with decreasing device width, W, even as there is no concurrent Hall resistance, R_{xy}, correction. A multi-conduction model, including negative diagonal-conductivity, and non-vanishing off-diagonal conductivity, was shown to reproduce the experimental observations. The results suggested that boundary scattering in the mm$wide 2DES with mm-scale electron mean-free-paths might be responsible for the observed "non-ohmic" size-dependent negative GMR.

- *Interaction of microwave radiation with the high mobility two-dimensional electron system in GaAs/AlGaAs heterostructures, A. N. Ramanayaka, T. Ye, H-C. Liu, W. Wegscheider, and R. G. Mani, Physica B 453, 43-48 (2014).*

The influence of microwave excitation on the magnetotransport properties of the high mobility two-dimensional electron system (2DES) in the GaAs/AlGaAs heterostructure system is investigated here by exploring (a) the dependence of the amplitude of the microwave-induced magnetoresistance-oscillations on the polarization direction of the linearly polarized microwaves and (b) the microwave reflection from the 2DES. The polarization study indicated that the amplitude of the magnetoresistance oscillations is remarkably responsive to the relative orientation between the linearly polarized microwaves and the current-axis in the specimen. At low microwave power, P, experiments indicated a strong sinusoidal variation in the diagonal resistance R_{xx} vs. θ at the oscillatory extrema of the microwave-induced magnetoresistance oscillations. The reflection study indicated strong correlations between the microwave induced magnetoresistance oscillations and oscillatory features in the microwave reflection in a concurrent measurement of the magnetoresistance and the microwave magnetoreflection from the 2DES. The correlations were followed as a function of the microwave frequency and the microwave power, and the results were reported.

- *Combined study of microwave-power/linear polarization dependence of the microwave radiation-induced magnetoresistance oscillations in GaAs/AlGaAs devices, T. Ye, H-C. Liu, W. Wegscheider, and R. G. Mani, Phys. Rev. B 89, 155307 (2014).*

This paper reported the results of a combined microwave polarization-dependence-and power- dependence study of the microwave radiation-induced magnetoresistance oscillations in high mobility GaAs/AlGaAs heterostructure devices at liquid helium temperatures. The diagonal resistance was measured with the magnetic field fixed at the extrema of the radiation-induced magnetoresistance oscillations, as the microwave power was varied at a number of microwave polarization angles. The results indicated a non-linear relation between the oscillatory peak- or valley- magnetoresistance and the microwave power, as well as a cosine square relation between the oscillatory peak- or valley- magnetoresistance and the microwave polarization angle. The main features were compared with the predictions of existing models and reasonable agreement was reported.

- *Magnetotransport characteristics of a two-dimensional electron system driven to negative conductivity by microwave photoexcitation, R. G. Mani and A. Kriisa, Scientific Reports 3, 3478 (2013)| doi:10.1038/srep03478.*

Negative diagonal magneto-conductivity/resistivity is a spectacular- and thought provoking- property of driven, far-from-equilibrium, low dimensional electronic systems. The physical response of this exotic electronic state is not yet fully understood since it is rarely encountered in experiment. The microwave-radiation-induced zero-resistance state in the high mobility GaAs/AlGaAs 2D electron system is believed to be an example where negative magneto-conductivity/resistivity is responsible for the observed phenomena. Here, we examined the magneto-transport characteristics of this negative conductivity/resistivity state in the microwave photo-excited two-dimensional electron system (2DES) through a numerical solution of the associated boundary value problem. The results suggested, surprisingly, that a bare negative diagonal conductivity/resistivity state in the 2DES under photo-excitation should yield a positive diagonal resistance with a concomitant sign reversal in the Hall voltage.

- *Microwave reflection study of ultra high mobility GaAs/AlGaAs 2D electron system at large filling factors, T. Ye, R. G. Mani, and W. Wegscheider, MRS Proceedings, 1635, pp 69-74 (2014)| doi: 10.1557/opl.2014.107*

Here, the microwave-induced magnetoresistance oscillations exhibited by the GaAs/AlGaAs two dimensional electron system (2DES) were further examined under microwave and terahertz photo-excitation at liquid helium temperatures. In order to identify the relative physical contributions, we concurrently examined magnetotransport and microwave reflection from the 2DES. For the reflection measurements, a sensitive microwave detector was assimilated into the standard experimental setup. We correlated changes in reflection with the concurrent transport response of the photo-excited 2DES.

People working on the project:

The manpower within the PI's group last summer (2013) consisted of the PI (R. G. Mani), and five plus one graduate students (T. Ye, Olesya Sarajlic, Han-Chun Liu, and Zhuo Wang, and Kapil Baral at GSU and A. Kriisa at Emory University).

Kapil Baral left the group in Fall 2013. Olesya Sarajlic left with the MS degree in Dec. 2013. New students Dave O'Brien and Monica Cook joined the group in Summer 2014.

Summary for the period 2012 – 2013:

In the above mentioned period, this funding helped to produce the publications listed below:

7) "Mesoscale scanning electron and tunneling microscopy study of the surface morphology of thermally annealed copper foils for graphene growth," O. Sarajlic and R. G. Mani, Chem. Of Mat'l. 25, 1643 (2013).

8) "Remotely sensed transport in microwave photoexcited GaAs/AlGaAs two-dimensional electron system," T. Ye, R. G. Mani, and W. Wegscheider, Appl. Phys. Lett. 102, 242113 (2013).

9) "Terahertz photovoltaic detection of cyclotron resonance in the regime of radiation-induced magnetoresistance oscillations," R. G. Mani, A. Ramanayaka, T. Ye, M. Heimbeck, H. Everitt, and W. Wegscheider, Phys. Rev. B 87, 245308 (2013).

10) "Observation of resistively detected hole spin-resonance and zero-field pseudo spin splitting in epitaxial graphene", Nature Comm. 3, 996 (2012). [DOI:10-1038/ncomms1986].

This graphene work (4) received attention by the media. A publication of the press release for this work can be found, for example, at the following links:

http://finchannel.com/Main_News/B_Schools/114204_Physicists_explore_properties_of_electrons_in_revolutionary_material/
http://www.sciencedaily.com/releases/2012/08/120810112810.htm
http://www.ecnmag.com/news/2012/08/physicists-explore-properties-electrons-revolutionary-material
http://phys.org/news/2012-08-physicists-explore-properties-electrons-graphene.html
http://www.eurekalert.org/pub_releases/2012-08/gsu-pep081012.php
http://esciencenews.com/articles/2012/08/10/physicists.explore.properties.electrons.revolutionary.material
http://www.sciencenewsline.com/summary/2012081014510004.html
http://www.bio-medicine.org/biology-news-1/Physicists-explore-properties-of-electrons-in-revolutionary-material-26268-1/
http://www.sciencecodex.com/physicists_explore_properties_of_electrons_in_revolutionary_material-96374

http://www.rdmag.com/News/2012/08/Materials-Science-Physics-Graphene-Physicists-explore-spin-properties-of-electrons-in-graphene/
http://phys.org/news/2012-08-physicists-explore-properties-electrons-graphene.html
http://www.nanowerk.com/news2/newsid=26290.php
http://www.brightsurf.com/news/headlines/78312/_Physicists_explore_properties_of_electrons_in_revolutionary_material_.html
http://m.phys.org/news/2012-08-physicists-explore-properties-electrons-graphene.html
http://www.hydrogenfuelnews.com/graphene-research-gets-a-boost-with-new-examination-method/855219/
http://www.azom.com/news.aspx?newsID=33827

Four conference papers listed below were submitted but not yet published in the Proceedings of the 31th International Conference on the Physics of Semiconductors 2012, which was held in Zurich, Switzerland:

- "Electron heating due to microwave photoexcitation in the high mobility GaAs/AlGaAs two dimensional electron system," A. N. Ramanayaka, R. G. Mani, and W. Wegscheider.

- "Observation of linear-polarization sensitivity in the microwave radiation-induced magnetoresistance oscillations," R. G. Mani, A. N. Ramanayaka, and W. Wegscheider.

- "Study of reflection and transport in the microwave photo-excited GaAs/AlGaAs two dimensional electron system", T. Ye, R. G. Mani, and W. Wegscheider.

- "Topological Hall Insulator," A. Kriisa, R. G. Mani, and W. Wegscheider.

These conference papers go together with the following posters presented at 31th International Conference on the Physics of Semiconductors 2012 in Zurich, Switzerland.

- Electron heating due to microwave photoexcitation in the high mobility gaas/algaas two dimensional electron system**,** A. N. Ramanayaka, R. G. Mani, and W. Wegscheider.
- Topological Hall Insulator, A. Kriisa, R. G. Mani, and W. Wegscheider, 31th International Conference on the Physics of Semiconductors 2012, 29 July – 3 August 2012, Zurich, Switzerland.
- Magnetoresistance in the topological insulator Bi_2Te_3, P. Kumar, A. Ramanayaka, and R. G. Mani, 31th International Conference on the Physics of Semiconductors 2012, 29 July – 3 August 2012, Zurich, Switzerland.
- Study of reflection and transport in the microwave photoexcited GaAs/AlGaAs two dimensional electron system, T. Ye, R. G. Mani, and W. Wegscheider, 31th International Conference on the Physics of Semiconductors 2012, 29 July – 3 August 2012, Zurich, Switzerland.
- Observation of linear-polarization-sensitivity in the microwave-radiation-induced magnetoresistance oscillations, R. G. Mani, A. N. Ramanayaka, and W. Wegscheider, 31th International Conference on the Physics of Semiconductors 2012, 29 July – 3 August 2012, Zurich, Switzerland.

In the summer of 2013, the group presented two posters at the 20th International Conference on Electronic Properties of Two-dimensional Systems in Wroclaw, Poland.

- Linear polarization rotation study of the microwave radiation-induced magnetoresistance oscillations in the GaAs/AlGaAs system, A. N. Ramanayaka, T. Ye, H. C. Liu, R. G. Mani, and W. Wegscheider.
- Nonlinear growth in the microwave reflection signal from the GaAs/AlGaAs 2DES in the regime of radiation-induced magnetoresistance oscillations, Tianyu, Ye, R. G. Mani, and W. Wegscheider.

Finally, there was one poster at the XXII International Materials Research Conference in Cancun, Mexico.

- Microwave Reflection from the Microwave Photo-Excited High Mobility GaAs/AlGaAs Two-Dimensional Electron System, Tianyu Ye, R. G. Mani, and W. Wegscheider.

The PI, Ramesh Mani, presented an invited talk entitled "Microwave transport study of the GaAs/AlGaAs 2DES and epitaxial graphene" at the International Workshop "MIRO and all that," 13 - 16 May, 2013, in Montpellier, France. He presented a talk entitled "Resistively Detected Spin Resonance and Zero-field Pseudo Spin Splitting in Epitaxial Graphene" at the 20th International conference on Electronic Properties of Two-dimensional Systems, July 1 - 5, 2013, in Wroclaw, Poland. He presented a pair of talks entitled (i) Resistively Detected Spin Resonance and Zero-field Pseudo Spin Splitting in Epitaxial Graphene, and (ii) Linear polarization rotation study of the microwave-induced magnetoresistance oscillations in the GaAs/AlGaAs system at the XXII International Material Research Congress 2013 (IMRC 2013), August 11 -15, 2013, in Cancun, Mexico.

In the winter of 2013, there were five talks by group members at the 2013 March Meeting of the American Physical Society in Baltimore, MD, in the week of February 27-March 2. Associated abstract reference is given below.

- Electrically detected spin resonance in epitaxial graphene, R. G. Mani, J. Hankinson, C. Berger, and W. A. de Heer, Bull. Am. Phys. Soc. 58, Abstract: BAPS.2013.MAR.J7.2, March 19, 2013.
- Study of the phase-shift in the linear-polarization-angle dependence of the microwave radiation-induced magnetoresistance oscillations in the GaAs/AlGaAs system, Han-chun-Liu, T. Ye, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 58, Abstract: BAPS.2013.MAR.A42.2, March 18, 2013.
- Study of the correlation between microwave reflection and microwave-induced magnetoresistance oscillations in the GaAs/AlGaAs two dimensional electron system, Tianyu Ye, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 58, Abstract: BAPS. 2013.MAR.A42.1, March 18, 2013.
- Magnetoresistance in thin Bi2Te3 layers contacted by Indium (In) superconducting electrodes, Zhuo Wang and R. G. Mani, Bull. Am. Phys. Soc. 58, Abstract: BAPS.2013.MAR.J12.4, March 19, 2013.
- Immense weak localization effect in CVD graphene, O. Sarajlic and R. G. Mani, Bull. Am. Phys. Soc. 58, Abstract BAPS.2013.MAR.W5.11, March 21, 2013.

In the summer of 2012, graduate student Aruna Ramanayaka successfully presented and defended his Ph.D. theses thereby obtaining his Ph.D. Graduate student Tianyu Ye obtained his M.S. in Physics in May 2013.

Summary of Publications:

- *"Observation of resistively detected hole spin-resonance and zero-field pseudo spin splitting in epitaxial graphene", Nature Comm. 3, 996 (2012). [DOI:10-1038/ncomms1986].* This paper presents the first experimental observation of spin resonance by electrical detection in a graphene nanostructure. The measurements examined epitaxial graphene prepared by heat treating SiC wafers. Small chips were prepared into Hall bars by electron beam lithography. The devices included Gold-palladium contacts. The samples were cooled to liquid helium temperatures and excited with microwaves over the 10- 50 Ghz band, and the electrical response was detected both in the presence and absence of microwave excitation. Most surprisingly, the devices exhibited a strong microwave response! At the most basic level, it looks like a graphene device can be used as a microwave power sensor! The reason for the strong electron heating, unlike in GaAs/AlGaAs is not yet understood. But, nevertheless, it turns out that heating is reduced under spin resonance conditions, and this helps to detect the spin resonance. A second interesting and unexpected feature in the experiment was that there occurred two spin resonance branches in this system. This effect was attributed to the breaking of the spin- and sublattice- degeneracy in the honeycomb graphene system. In such a picture, the measurements reveal the sublattice splitting in the epitaxial graphene system. We expect further publications from very rich and interesting results in this system.

- *"Terahertz photovoltaic detection of cyclotron resonance in the regime of radiation-induced magnetoresistance oscillations," Phys. Rev. B 87, 245308 (2013).* This paper represents joint work with Army scientists H. O. Everitt and M. Heimbeck of the Redstone Arsenal in Alabama. The work arose from efforts to test the performance of their commercially manufactured daisy-chained frequency multipliers which help to realize radiation upto 780 GHz. At the highest frequency, these sources produce 0.3 – 0.6 mW of radiation. Using these sources, we examined and compared the diagonal magnetoresistance, R_{xx}, and the photo-voltage induced by microwave ($42 < f < 300$ GHz) and terahertz ($f > 300$ GHz) photoexcitation in the high mobility quasi two-dimensional GaAs/AlGaAs system. The ultra high mobility ($\mu \sim 10{,}000{,}000$ cm^2/Vs) GaAs/AlGaAs is known to exhibit magnetoresistance oscillations under photoexcitation, where the period of the oscillations in the inverse magnetic field is inversely proportional to the radiation frequency. The aim of the study was to examine associated phenomena into the terahertz band using these new radiation sources. The data presented in this work helped to demonstrate strong radiation-induced magneto-resistance oscillations in R_{xx} to 360 GHz, a new record for this phenomenon. In addition, cyclotron resonance was observed in the microwave and terahertz photo-voltage to 725 GHz. These results helped to show that our high mobility GaAs/AlGaAs 2DES specimens emain photo-active in magnetotransport into the terahertz band.

- "*Remotely sensed transport in microwave photoexcited GaAs/AlGaAs two-dimensional electron system,*" *Appl. Phys. Lett. 102, 242113 (2013).* This work addressed the question whether any correlates to the radiation-induced magnetoresistance oscillations in the high mobility GaAs/AlGaAs system may be observed in the reflected radiation. It turns out that most of the existing works have not extensively examined the transmitted or reflected radiation in this 2d electron system subjected to a weak transverse magnetic field. Our study showed, remarkably, a strong correlation between the magnetoresistive response of the microwave photo-excitedGaAs/AlGaAs 2D electron system and the concurrent microwave reflection from the 2DES. Thus, we followed these correlations as a function of the microwave power, the microwave frequency, and the applied current in the GaAs/AlGaAs Hall bar specimen. We found, strikingly, that the character of the reflection signal remains unchanged even when the current is switched off in the GaAs/AlGaAs Hall bar specimen. This is a surprising result since many theories have asserted that the radiation-induced magnetoresistance oscillations result from scattered electron currents and they have implied the absence of a signature in the magnetoreflection in the absence of an applied current. Our results show, therefore, a perceptible microwave-induced change in the electronic properties of the 2DES, even in the absence of an applied current.
- "*Mesoscale scanning electron and tunneling microscopy study of the surface morphology of thermally annealed copper foils for graphene growth,*" *O. Sarajlic and R. G. Mani, Chem. Of Mat'l. 25, 1643 (2013).* Graphene is a very promising material for the development of detectors and modulators operating in the terahertz region of the electromagnetic spectrum. A problem with this system has been, however, realizing high quality and large size material for device applications. Several methods have been utilized to realize graphene, these include the epitaxial growth on SiC, exfoliation of small flakes from graphite, and chemical vapor deposition (CVD). The CVD approach, which yields centimeter size graphene sheets, typically utilizes heated foils of copper or nickel that are exposed to organic compounds. The question explored in this paper is: how does the quality of the copper foil surface influence graphene growth by CVD. Thus, we investigated the effects of thermal annealing of polycrystalline Cu foil at the mesoscale using an ultrahigh vacuum (UHV) scanning tunneling microscope (STM), a scanning electron microscope (SEM), and an optical microscope, to determine the structure of the foil surface as a function of treatment. We examined the relative grain size and relative flatness of the substrate, before and after annealing. These optical studies showed that the Cu surface is very rough and granular on the atomic scale.

People working on the project:

The manpower within the PI's group in summer 2012 consisted of the PI (R. G. Mani), and five plus one graduate students (A. Ramanayaka, T. Ye, Olesya Sarajlic, Han-Chun Liu, and Zhuo Wang at GSU and A. Kriisa at Emory University), and three undergraduate students (Jennifer Rehm, Kenny Lee, and Terence Fisher).

Kapil Baral joined the group in Summer 2012, as graduate student Aruna Ramanayaka graduated and found a post-doc position elsewhere.

Summary for the period 2011-2012:

In the above mentioned period, this funding helped to produce the publications listed below:

11) "Observation of linear-polarization-sensitivity in the microwave-radiation-induced magnetoresistance oscillations, R. G. Mani, A. N. Ramanayaka, and W. Wegscheider, Phys. Rev. B 84, 085308 (2011).
12) "Linear-polarization-rotation-response in the microwave-radiation-induced magneto-resistance oscillations", A. N. Ramanayaka, R. G. Mani, J. Inarrea, and W. Wegscheider, Phys. Rev. B. 85, 205315 (2012).
13) "Observation of resistively detected hole spin-resonance and zero-field pseudo spin splitting in epitaxial graphene", Nature Comm. 3, 996 (2012). [DOI:10-1038/ncomms1986].

    This graphene work has received attention by the media. A publication of the press release for this work can be found, for example, at the following links:

http://finchannel.com/Main_News/B_Schools/114204_Physicists_explore_properties_of_electrons_in_revolutionary_material/
http://www.sciencedaily.com/releases/2012/08/120810112810.htm
http://www.ecnmag.com/news/2012/08/physicists-explore-properties-electrons-revolutionary-material
http://phys.org/news/2012-08-physicists-explore-properties-electrons-graphene.html
http://www.eurekalert.org/pub_releases/2012-08/gsu-pep081012.php
http://esciencenews.com/articles/2012/08/10/physicists.explore.properties.electrons.revolutionary.material
http://www.sciencenewsline.com/summary/2012081014510004.html
http://www.bio-medicine.org/biology-news-1/Physicists-explore-properties-of-electrons-in-revolutionary-material-26268-1/
http://www.sciencecodex.com/physicists_explore_properties_of_electrons_in_revolutionary_material-96374
http://www.rdmag.com/News/2012/08/Materials-Science-Physics-Graphene-Physicists-explore-spin-properties-of-electrons-in-graphene/
http://phys.org/news/2012-08-physicists-explore-properties-electrons-graphene.html
http://www.nanowerk.com/news2/newsid=26290.php
http://www.brightsurf.com/news/headlines/78312/_Physicists_explore_properties_of_electrons_in_revolutionary_material_.html
http://m.phys.org/news/2012-08-physicists-explore-properties-electrons-graphene.html
http://www.hydrogenfuelnews.com/graphene-research-gets-a-boost-with-new-examination-method/855219/
http://www.azom.com/news.aspx?newsID=33827

In the summer of 2011, the group presented the following pair of posters at the Electronic Properties of Two-dimensional systems conference in Tallahassasee, FL.

- Remote sensing of transport under microwave photo-excitation in the two-dimensional electron system (Mo-P-48) by T. Ye, A. Ramanayaka, R. G. Mani, and W. Wegscheider, EP2DS19/MSS15 Conference, 7/25 – 7/29 2011, Tallahassee, FL.
- Microwave-induced electron-heating in the regime of the radiation-induced magnetoresistance oscillations in the GaAs/AlGaAs 2D electron system (Tu-

P-82) by A. Ramanayaka, R. G. Mani, and W. Wegscheider, EP2DS19/MSS15 Conference, 7/25 – 7/29 2011, Tallahassee, FL. 109)

Ramesh Mani presented the following invited talk at the DOE-BES meeting in Rockville, MD: Microwave- and Terahertz- Photo-Excited Transport in Low-Dimensional Electron Systems (Invited Speaker). DOE BES - Experimental Condensed Matter Physics , Rockville, MD. 8/10/2011.

Ramesh Mani attended the 2011 Nano-DDS conference and presented a talk entitled: Photo-excited transport in epitaxial graphene as a platform speaker. The group also presented a pair of posters listed below:

- Method for measuring the electron temperature in microwave photo-excited two-dimensional electron systems by A. Ramanayaka, R. G. Mani, and W. Wegscheider, Nano-DDS 2011 Conference, 8/30/2011, Brooklyn, NY, and
- Microwave reflection from the microwave photo-excited two-dimensional electron system by T. Ye, A. Ramanayaka, R. G. Mani, and W. Wegscheider, Nano-DDS 2011 Conference, 8/30/2011, Brooklyn, NY.

In the Fall of 2011, The PI, Ramesh Mani, presented an invited talk entitled "Photo-excited transport in epitaxial graphene" at the 3rd International Symposium on the Science and Technology of Epitaxial Graphene, 24-27 Oct. 2011, in St. Augustine, FL.

In the winter of 2012, there were five talks by group members at the 2012 March Meeting of the American Physical Society in Boston, MA, in the week of February 27-March 2. Associated abstract titles are given below.

- Observation of linear polarization sensitivity in the microwave-radiation induced magneto-resistance oscillations, R. G. Mani, A. Ramanayaka, and W. Wegscheider, Bull. Am. Phys. Soc. 57, Abstract # W24.00010, March 1, 2012.

- Linear polarization rotation study of the radiation-induced magnetoresistance oscillations, A. Ramanayaka, R. G. Mani, J. Inarrea, and W. Wegscheider, Bull. Am. Phys. Soc. 57, Abstract # W24.00013, March 1, 2012.

- Microwave reflection study of GaAs/AlGaAs devices in the regime of the radiation-induced magnetoresistance oscillations, Tianyu Ye, A. Ramanayaka, R. G. Mani, J. Inarrea, and W. Wegscheider, Bull. Am. Phys. Soc. 57, Abstract # W24.00009, March 1, 2012.

- Mesoscale STM study of thermally annealed copper foils, Olesya Sarajlic and R. G. Mani, Bull. Am. Phys. Soc. 57, Abstract # T12.00006, Feb. 29, 2012.

- Magnetotransport study of the topological insulator Bi_2Te_3, P. Kumar, A. Ramanayaka, and R. G. Mani, Bull. Am. Phys. Soc. 57, Abstract # J31.00008, Feb. 28, 2012.

Here, abstract #5, "Magnetotransport study of the topological insulator Bi_2Te_3," represents our first talk on our topological insulator related research. Abstract #2, "Mesoscale STM study of thermally annealed copper foils," represents the results of our study of the graphene growth process by Chemical Vapor Deposition on copper foils.

In the Spring of 2012, a set of talks and posters were Talks and posters presented at the NPCQS International Workshop on Nonequilibrium Phenomena in Complex Quantum Systems in Okinawa, Japan April 23-27, 2012. The PI, Ramesh Mani, presented an invited talk entitled “Zero-resistance states induced by electromagnetic wave excitation in 2D electron systems.” The senior graduate student, Aruna Ramanayaka, presented a contributed talk entitled, “Polarization rotation study of the radiation-induced magneto-resistance oscillations,” A. N. Ramanayaka. There were also posters entitled:

- Study Of The Electron Temperature In The Microwave Photo-Excited GaAs/AlGaAs Two Dimensional Electron System, by A. N. Ramanayaka, R. G. Mani, W. Wegscheider .
- Concurrent study of microwave reflection and transport in the microwave photo-excited high mobility GaAs/AlGaAs two-dimensional electron system, by Tianyu Ye, R. G. Mani, W. Wegscheider , and
- Photoexcited Transport In Graphene, by Olesya Sarajlic, R. G. Mani, J. Hankinson, C. Berger, and W. de Heer**.** Ramesh Mani also served as Conference Session Chairman: International Workshop on Nonequilibrium Phenomena in Complex Quantum Systems (NPCQS2012) for the Session on ESR and Spin qubits, on April 25, 2012, in Okinawa, Japan.

In the summer of 2012, a talk and a series of posters were presented at the The 20th International Conference on "High Magnetic Fields in Semiconductor Physics, HMF-20, that was held in Chamonix Mont-Blanc, France, from 22 - 27 July, 2012. The talk by Ramesh Mani was entitled “Linear polarization sensitivity and electron heating in the regime of radiation-induced magnetoresistance oscillations”.
The posters were entitled:

- Microwave reflection and transport in the microwave photo-excited high mobility GaAs/AlGaAs two-dimensional electron system by Tianyu Ye, A. N. Ramanayaka, R. G. Mani, W. Wegscheider,
- Study of microwave electron heating in the high mobility GaAs/AlGaAs two dimensional electron system at large filling factors by A. N. Ramanayaka, R. G. Mani, and W. Wegscheider, and
- Microwave photo-excited transport in epitaxial graphene by R. G. Mani, O. Sarajlic,J. Hankinson, C. Berger, and W. de Heer

A pair of students, Aruna Ramanayaka and Prakash Thapa, obtained their M.S. in Physics over the last year. In the summer of 2012, graduate student Aruna Ramanayaka successfully presented and defended his Ph.D. theses thereby obtaining his Ph.D.

Summary of Publications:

- *“Observation of linear-polarization-sensitivity in the microwave-radiation-induced magnetoresistance oscillations, R. G. Mani, A. N. Ramanayaka, and W. Wegscheider, Phys. Rev. B 84, 085308 (2011).* This paper provides the first experimental demonstration of the strong sensitivity of the radiation-induced magnetoresistance oscillations to the relative orientation of the linear polarization of the microwaves with respect to the GaAs/AlGaAs device. We note that experimental microwave polarization studies in this context are difficult to carry out since it is non-trivial to rotate, in-situ, a specimen with wires over 360^0 at the end of a 2 meter long sample holder, within a small (~ 30mm) diameter low temperature cryostat. To overcome this barrier, we have developed, instead, a setup where the wired sample remains fixed within the cryostat, while the microwave polarization is rotated with respect to the sample, from outside the cryostat. To achieve this capability, the canonical rectangular waveguide was replaced with a circular (~ 11mm i.d.) waveguide, and a rotatable coax-to-waveguide-adapter, probe-coupled, electric-monopole-antenna, microwave-launcher was developed to couple microwaves into the waveguide. Here, the angular position of the MW-antenna could be set as desired and then locked in place with a clamped quick connect. The Hall bar sample was mounted at the low temperature (T=1.5K) end of the circular waveguide, and the long axis of the device was oriented parallel to polarization axis of the MW-antenna. In this way, we could set and change as desired the angle of the MW-antenna with respect to the device long-axis. The effort involved in developing the setup was well worth it because the experiments provided ground breaking results in the field, providing the first clear evidence for linear polarization sensitivity in the microwave radiation-induced magnetoresistance oscillations. The result is interesting because many theories exist for the radiation induced magnetoresistance oscillations and they make widely different predictions regarding the polarization sensitivity of the effect.

- *"Linear-polarization-rotation-response in the microwave-radiation-induced magneto-resistance oscillations", A. N. Ramanayaka, R. G. Mani, J. Inarrea, and W. Wegscheider, Phys. Rev. B. 85, 205315 (2012).* This paper presents more detailed measurements of the polarization sensitivity of the microwave and terahertz radiation-induced magnetoresistance oscillations. The novelty here was that the resistive response was examined at fixed magnetic fields as a function of the polarization angle with respect to the device axis. Thus, we fixed the magnetic field at the peaks or valleys of the magneto-resistance oscillations and obtained quasi-continuous curves of the response vs. the angle. We found, surprisingly, at low microwave power, P, a strong sinusoidal response as $R_{XX}(\theta) = A \pm C \cos^2(\theta - \theta_0)$ vs. the polarization rotation angle, θ, with the '+' and '-' cases describing the maxima and minima, respectively. At higher P, the principal resistance minimum exhibits additional extrema vs. θ. Notably, the phase shift θ_0 varies with f, B, and sgn(B). Again, the results differed widely from some theoretical predictions.
- *"Observation of resistively detected hole spin-resonance and zero-field pseudo spin splitting in epitaxial graphene", Nature Comm. 3, 996 (2012). [DOI:10-1038/ncomms1986].* This paper presents the first experimental observation of spin resonance by electrical detection in a graphene nanostructure. The measurements examined epitaxial graphene prepared by heat treating SiC wafers. Small chips were prepared into Hall bars by electron beam lithography. The devices included Gold-palladium contacts. The samples were cooled to liquid helium temperatures and excited with microwaves over the 10- 50 Ghz band, and the electrical response was detected both in the presence and absence of microwave excitation. Most surprisingly, the devices exhibited a strong microwave response! At the most basic level, it looks like a graphene device can be used as a microwave power sensor!. The reason for the strong electron heating, unlike in GaAs/AlGaAs is not yet understood. But, nevertheless, it turns out that heating is reduced under spin resonance conditions, and this helps to detect the spin resonance. A second interesting and unexpected feature in the experiment was that there occurred two spin resonance branches in this system. This effect was attributed to the breaking of the spin- and sublattice- degeneracy in the honeycomb graphene system. In such a picture, the measurements reveal the sublattice splitting in the epitaxial graphene system. We expect further publications from very rich and interesting results in this system. Finally, it

appears worth noting that we have established a good working relationship with Prof. W. De Heer's group at the Georgia Institute of Technology to obtain state of the art epitaxial graphene.

People working on the project:

The manpower within the PI's group in summer 2011 consisted of the PI (R. G. Mani), one post-docs (P. Kumar), three plus one graduate students (A. Ramanayaka, T. Ye and P. Thapa at GSU and A. Kriisa at Emory University), and four undergraduate students (J. Abreus, Megan Smith, Justin Chastain, Olesya Sitnikova-Sarajlic.).

Olesya Sitnikova-Sarajlic, Han-Chun Liu, and Zhuo Wang joined the group in the Fall 2011 semester as new graduate students. There were also several new undergraduate students over the 2011-2012 academic year including Jennifer Rehm, Kailani Redding, Kenny Lee, and Terence Fisher. Unfortunately, the post-doc P. Kumar returned to India in July 2012. Further, A. Ramanayaka and P. Thapa graduated in the Summer of 2012. A new graduate student, K. Baral, joined the group beginning in the Fall 2012 semester.

Infrastructure:

Some new equipment infrastructure was added to the group over this last year. The major new equipment consists of an electron beam writer for the existing Scanning Electron Microscope (SEM). The SEM has provided wonderful new imaging capability into the nanoscale within the laboratory. The electron beam writer should soon provide the capability to carry out electron beam lithography for producing very small specimens. This will be very useful for manufacturing graphene devices. Other new infrastructure include a pair of small CVD systems to prepare CVD graphene.

Summary for the period 2010-2011:

In the above mentioned period, this funding helped to produce six publications, these papers are listed below:

14) "Transport study of Berry's phase, the resistivity rule, and quantum Hall effect in graphite," A. Ramanayaka and R. G. Mani, Phys. Rev. B 82, 165327 (2010).

15) "Hall effects in doubly connected specimens," A. Kriisa, R. G. Mani, and W. Wegscheider, IEEE Trans. In Nanotechnology 10, 179 (2011).

16) "Comparative study of microwave radiation-induced magnetoresistance oscillations in GaAs/AlGaAs devices," R. G. Mani and W. Wegscheider, IEEE Trans. In Nanotechnology 10, 170 (2011).

17) "Sublinear radiation power dependence of photoexcited resistance oscillations in two dimensional electron systems," J. Inarrea, R. G. Mani, and W. Wegscheider, Phys. Rev. B 82, 205321 (2010).

18) "Microwave induced electron heating in the regime of the radiation-induced magnetoresistance oscillations", A. Ramanayaka, R. G. Mani, and W. Wegscheider, Phys. Rev. B. 83, 165303 (2011).

19) “Observation of linear-polarization-sensitivity in the microwave-radiation-induced magnetoresistance oscillations, R. G. Mani, A. N. Ramanayaka, and W. Wegscheider, Phys. Rev. B 84, 085308 (2011). [This paper appeared shortly after the end of the reporting period]

There were also five talks by group members at the 2011 March Meeting of the American Physical Society in Dallas, TX, in the week of March 21-25, 2011. Associated abstract titles are given below.

- “Transport study under microwave photoexcitation in epitaxial Graphene,” R. G. Mani, J. Hankinson, C. Berger, and W. de Heer, Bull. Am. Phys. Soc. 56, Abstract# x11.00004, March 24, 2011
- “Scanning Tunneling Microscope study of Atomic steps in Gold films on Muscovite Graphite,” Olesya Sitnikova and R. G. Mani, Bull. Am. Phys. Soc. 56, Abstract# W21.00004, March 24, 2011
- “Microwave induced electron heating in the regime of the radiation-induced magnetoresistance oscillations,” A. Ramanayaka, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 56, Abstract# x11.00003, March 24, 2011
- “Remote sensing of transport in microwave photo-excited magnetoresistance oscillations in the GaAs/AlGaAs system,” Tianyu Ye, G. Chand, A. Ramanayaka, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 56, Abstract# x11.00006, March 24, 2011
- “Microwave photo-voltaic oscillations in the GaAs/AlGaAs system,” G. Chand, T. Ye, A. Ramanayaka, R. G. Mani, and W. Wegscheider, Bull. Am. Phys. Soc. 56, Abstract# x11.00011, March 24, 2011

Here, the abstract, “Transport study under microwave photoexcitation in epitaxial Graphene,” represents our first talk on our Graphene related research. Abstract #2, “Scanning Tunneling Microscope study…,” was presented by an undergraduate physics student, Olesya Sitnikova.

A pair of posters were presented at the 2nd International Symposium on the Science and Technology of Epitaxial Graphene (STEG2), Sept. 14-17, 2010, in Amelia Island, Florida. The titles of these posters are given below: “Mesoscale STM study of epitaxial Graphene,” by P. Kumar, M. Anquez, R. G. Mani, J. Hankinson, C. Berger, and W. de Heer. And “Transport study of graphite,” by A. N. Ramanayaka, and R. G. Mani.

A pair of posters were presented at the EP2DS-2011 Conference in Tallahassee, FL in the week of 7/25/2011 – 7/29/2011. These posters were entitled “Remote sensing of transport under microwave photoexcitation in the two dimensional electron system” by T. Ye, A. Ramanayaka, R. G. Mani, and W. Wegscheider and “Microwave-induced electron heating in the regime of the radiation-inudced magnetoresistance oscillations in the GaAs/AlGaAs 2D electron system” by A. Ramanayaka, R. G. Mani, and W. Wegscheider.

A talk by Ramesh Mani entitled “Electron-microwave coupling in the GaAs/AlGaAs two dimensional electron system,” was scheduled at the 11th International Conference on the Physics of Light-Matter Coupling in Nanostructures, 4 – 8 April 2011 in Berlin, Germany. However, Ramesh Mani was unable to find a replacement to carry out his teaching duties, and therefore could not attend the meeting.

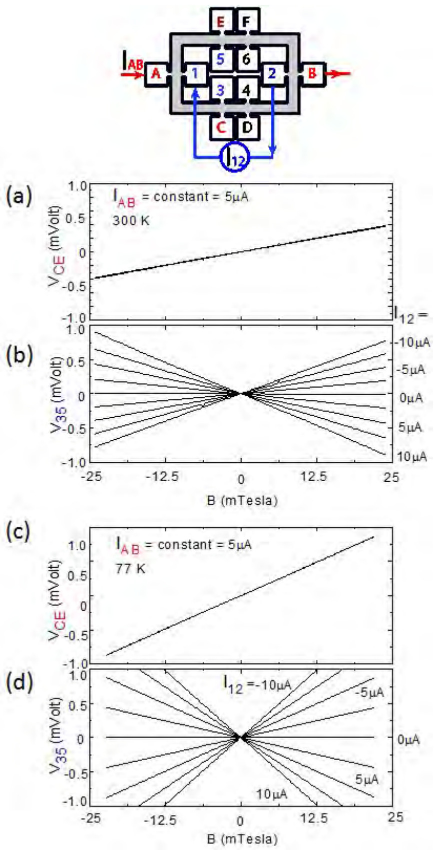

Fig. 1. Top: The measurement configuration in the "anti-hall bar within a Hall bar" geometry. Panels (a) and (b) represent a dual current experiment at T = 300 K, where a constant current of 5 μA is applied via the exterior contacts (A, B), as the current via the interior contacts (1, 2) is spanned from -10 to 10 μA. Here, two Hall voltages, V_{CE}, see panel (a), and V_{35}, see panel (b), are observed simultaneously. The Hall voltage on the external boundary V_{CE} remains unchanged as the Hall voltage on the interior boundary V_{35} varies in proportion to current applied via contacts (1, 2). Panels (c) and (d) represent measurements similar to panels (a) and (b), with the difference that the sample is now submerged into liquid nitrogen at T = 77 K. The steeper slope observed at lower temperatures reflects the lower carrier density at 77 K than at 300 K.

Instead, a poster entitled "Electron-microwave coupling in the GaAs/AlGaAs two dimensional electron system," by R. G. Mani and W. Wegscheider, was presented at The 7th International Conference on Low Dimensional Structures and Devices, 24 May 2011, Telchac, Nuevo Yucatan, Mexico, after the end of the academic semester.

An invited talk entitled "Microwave- and Terahertz-Photo-Excited Transport in Low-Dimensional Electron Systems," was presented at the DOE BES - Experimental Condensed Matter Physics Meeting in Rockville, MD.

Summary of Publications:

1) *"Transport study of Berry's phase, the resistivity rule, and quantum Hall effect in graphite," A. Ramanayaka and R. G. Mani, Phys. Rev. B 82, 165327 (2010).* As is known, graphite originates from the bernal stacking of layers of graphene, and graphite exhibits an anisotropic response with a large difference between the in-plane and perpendicular transport. Due to the close relation between graphite and graphene, some concepts proposed for graphene have also been invoked for graphite in the past. For example, some have argued for majority holes with a 2D Dirac spectrum in graphite. Further, Hall plateaus observed in van-der-Pauw measurements on highly oriented pyrolytic graphite (HOPG) have been cited as evidence for the integral quantum Hall effect (IQHE) in 3D graphite. Others have suggested simultaneous quantum Hall effects in graphite for the massive electrons and massless Dirac holes with Berry's phase of $\beta = 0$ and $\beta = 1/2$, respectively.

To investigate the similarities and differences between graphene and graphite, graphite samples were prepared from bulk Highly Oriented Pyrolytic Graphite (HOPG) using the scotch tape method. Low-frequency lock-in techniques were then utilized to measure both the diagonal (R_{xx}) and Hall (R_{xy}) resistances inside a He cryostat from 150 K down to 1.5 K in magnetic field (B), upto 10 T, parallel to the c-axis. The Hall Effect measurements indicated mobilities upto 14000 $cm^2V^{-1}s^{-1}$ at 1.5 K.

Transport measurements of HOPG showed strong Shubnikov-de Haas (SdH) oscillations and well defined plateau-like features in R_{xx} and R_{xy}, respectively. A comparative Shubnikov-de Haas-oscillations based Berry's phase analysis indicated, however, that graphite is unlike the GaAs/AlGaAs 2D electron system, the 3D n-GaAs epilayer, semiconducting $Hg_{0.8}Cd_{0.2}Te$, and some other systems. In particular, we found, surprisingly, that the infinite field phase (IFP) of Shubnikov-de Haas oscillations in graphite is empirically similar to the IFP in graphene, and unlike the IFP in the canonical semiconductor systems like InSb, GaAs/AlGaAs, GaAs, and HgCdTe. Since the IFP is linked to the Berry's phase, this feature identified the existence of Dirac-like charge carriers in 3D graphite.

"Hall effects in doubly connected specimens", A. Kriisa, R. G. Mani, and W. Wegscheider, IEEE Trans. In Nanotechnology 10, 179 (2011). The Hall effect is an old effect which still closely follows the original measurement configuration devised by E. H. Hall in the late 1800's. In the 20th century, after a close study of the Hall effect, van der Pauw identified four conditions for a proper Hall effect measurement. They are: (a) sample should be homogeneous in thickness, (b) contacts should be at the periphery of the specimen, (c) contacts should be sufficiently small, and (d) the Hall element should not include any holes within it. Thus, our work addressed the question: how is the Hall effect measurement modified when, for example, condition (d) of the van der Pauw's theorem is violated? To answer this question, we have carried out measurements on Hall bars with holes, and Hall bars with holes with current and voltage contacts within the hole. The latter configuration, known as the "anti-Hall-bar within a Hall bar," exhibits some remarkable Hall effect properties. For example, in this geometry, it becomes possible to realize a situation where the Hall effect does not reflect all the current within the specimen. It turns out that such properties are useful especially for the Hall effect based magnetic sensing applications. Below, we exhibit some experimental results to illustrate the characteristics.
Fig. 1. (a) and (b) show the measurements of the exterior and interior Hall voltages at T = 300 K, and Fig. 1(c) and (d) show the same at 77K, when two currents, one current via the interior and another current via exterior contacts, are simultaneously applied to the sample. Here, the exterior current I_{AB} is kept constant at 5 µA, and the interior current I_{12} is varied from -10 to 10 µA. We see that the exterior Hall voltage V_{CE} remains invariant to changes of interior current I_{12}, whereas interior Hall voltage V_{35} that appears across the hole, is linear in the magnetic field and exhibits proportionality to the interior applied currant I_{12}. Further, the interior Hall voltage vanishes for $I_{12} = 0$, and V_{CE} and V_{35} show opposite polarities for $I_{AB} = I_{12} = 5$ µA. Here, the electron density can be determined using the interior Hall effect by the relation $n=I_{12}B/eV_{35}$, where I_{12} (V_{35}) denote the interior current (voltage). The electron density can also be determined using the exterior Hall effect with the relation $n = I_{AB}B/eV_{CE}$. Note that the net current is not reflected in these Hall effects V_{35} and V_{CE}.

"Comparative study of microwave radiation-induced magnetoresistance oscillations in GaAs/AlGaAs devices," R. G. Mani and W. Wegscheider, IEEE Trans. In Nanotechnology 10, 170 (2011). This paper examined through experiment the inverse magnetic field periodic, radiation-induced magnetoresistance oscillations in GaAs/AlGaAs heterostructures prepared in W. Wegscheider's group, compared their characteristics with similar oscillations in V. Umansky's material, and described the variation in the lineshape of the radiation-induced oscillations with the microwave power, P, in the two materials. The results indicated consistent results for the two materials, and also unexpectedly identified a novel sublinear power law variation in the lineshape amplitude with P.

"Sublinear radiation power dependence of photoexcited resistance oscillations in two dimensional electron systems," J. Inarrea, R. G. Mani, and W. Wegscheider, Phys. Rev.

B 82, 205321 (2010). This paper represents a joint theoretical and experimental work investigating the sublinear growth in the amplitude, A, of the radiation-induced oscillations with the microwave power, P. Experiments indicated that the $A \propto P^{\alpha}$, where the exponent, α, decreased with decreasing temperature at liquid Helium temperatures, and, further, α, showed a small sensitivity to the microwave frequency. These results were modeled within the radiation-driven electron orbit model, where the radiation forces the orbit center of the Landau states to oscillate in the direction of the radiation electric field at the frequency of the microwave radiation. Since this theory indicates that the amplitude of the orbit center motion sets the amplitude, A, of the R_{XX} oscillations, and that the amplitude of the orbit center oscillation is proportional to the electric field, the theory was able to explain the observed exponent, $\alpha \sim \frac{1}{2}$. Further, the theory qualitatively modeled the observed variation in α with the temperature and the radiation-frequency.

"Microwave induced electron heating in the regime of the radiation-induced magnetoresistance oscillations", A. Ramanayaka, R. G. Mani, and W. Wegscheider, Phys. Rev. B. 83, 165303 (2011). This paper examined quantitatively the nature of electron heating due to microwave photo-excitation in the high mobility two dimensional electron systems by exploring the influence of microwave photoexcitation on the amplitude of Shubnikov-de Haas (SdH) oscillations in a regime where the cyclotron frequency, ω_c, and the microwave angular frequency, ω, satisfied $2\omega \leq \omega_c \leq 3.5\omega$. Specifically, the electron heating due to microwave excitation was extracted by comparing the damping of the amplitude of Shubnikov-de Haas oscillations due to microwave excitation with the damping of the same oscillations due to bath temperature changes in the dark. In good agreement with theoretical predictions, the results indicated $\Delta T_e/\Delta P \sim 9$mK/mW over the examined regime. That is, the microwaves do not appear to be heating the electronic system over this regime.

"Observation of linear-polarization-sensitivity in the microwave-radiation-induced magnetoresistance oscillations, R. G. Mani, A. N. Ramanayaka, and W. Wegscheider, Phys. Rev. B 84, 085308 (2011). This paper provides the first experimental demonstration of the strong sensitivity of the radiation-induced magnetoresistance oscillations to the relative orientation of the linear polarization of the microwaves with respect to the GaAs/AlGaAs device. The result is interesting because many theories exist for the radiation induced magnetoresistance oscillations and they make different predictions regarding the polarization sensitivity of the effect.

People working on the project:

The manpower within the PI's group in summer 2010 consisted of the PI (R. G. Mani), two post-docs (T. Ghanem and P. Kumar), one advanced student (M. Anquez), three plus one graduate students (A. Ramanayaka, T. Ye, and G. Chand at GSU and A. Kriisa at Emory University), and three undergraduate students (E. Appiah, J. Aiken, and H. Patel).

P. Thapa joined the group in Fall 2010 as a graduate student, as advanced student, M. Anquez, left the group and enrolled in the Physics graduate program at the Georgia Institute of Technology. The post-doc, T. Ghanem, returned home to Egypt in the Fall of 2010 due to some family issues. A new undergraduate student, Olesya Sitnikova, joined the group in Fall 2010. Another undergraduate, Tyler Thompson, was a member of the group for one semester, during the Spring of 2011, and helped to set up a CVD system. Three new graduate students joined the group in summer 2011. They are Olesya

Sitnikova-Sarajlic, Han-Chun Liu, and Zhuo Wang. There are also several new undergraduates working in the lab now. They are: Jose Abreus, Megan Smith, Justin Chastain.

Infrastructure:

Some new equipment infrastructure was added. The major new equipment included a Scanning Electron Microscope (SEM) and a Helium liquefier. The SEM provided new imaging capability into the nanoscale within the laboratory. The helium liquefier was purchased to help recover helium boiloff from the cryogenic cryostats and reduce the costs associated with the purchase of liquid Helium. In addition to the SEM and the liquefier, some microwave power sensors covering the range upto 50 GHz were also acquired to carry out microwave reflection studies of the high-mobility 2DES.

<u>Overall Summary:</u>

As can be seen above, this funding provided by the Army Research Office helped a junior faculty at Georgia State University, Dr. Ramesh Mani, develop his research program to the present situation which includes a fully outfitted low temperature, high magnetic field, and nanoscience laboratory that is capable of examining all facets of microwave and terahertz photo-excited transport in low dimensional systems. At the present, the research facility includes: A) a number of rf/microwave sources spanning the range 10 MHz – 120 GHz, a 40 GHz spectrum analyzer, microwave detectors to 50 GHz, B) a 14-Tesla magnet with variable temperature sample insert for 1.5 K – 300 K, a 30 mK dilution refrigerator, and a second 6T superconducting magnet system, C) A large complement of electronics including 7 lock-in amplifiers, various current and voltage sources, 12 GPIB capable DMM's, D) A three pocket e-beam evaporator, a thermal evaporator, and a rapid thermal annealer, E) Two plasma etchers, F) A UHV Scanning Tunneling Microscope, and an Atomic Force Microscope, G) A Scanning Electron Microscope outfitted with electron beam lithography capability, H) A pair of CVD deposition furnaces, I) a mask aligner and photoresist spinner, J) A wire bonder, K) a helium liquefier, and L) a pair of CVD growth systems capable of producing good quality CVD graphene and boron nitride. Over the same period, the manpower within the group has been variable. At the present state, the group consists of the PI, a post-doc, and six graduate students. It should be noted that papers have been authored by graduate students and talks have been presented regularly by both graduate and undergraduate students at national conferences. In sum, this ARO funding has helped to expand research and expose and train a new generation of students in downtown Atlanta, GA to the latest topics in the modern physics, applications, and technology of radiation from the microwave and terahertz bands. We thank the ARO for the support over the last four years.